

Understanding Single-Atom Catalysis in View of Theory

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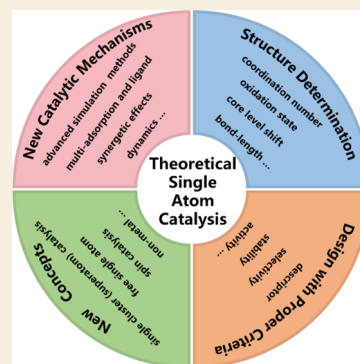
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ABSTRACT: In the past decade, isolated single atoms have been successfully dispersed on various substrates, with their potential applications being intensively investigated in different reactions. While the essential target of research in single-atom catalysis is the precise synthesis of stable single-atom catalysts (SACs) with clear configurations and impressive catalytic performance, theoretical investigations have also played important roles in identifying active sites, revealing catalytic mechanisms, and establishing structure–activity relationships. Nevertheless, special attention should still be paid in theoretical works to the particularity of SACs. In this Perspective, we will summarize the theoretical progress made on the understanding of the rich phenomena in single-atom catalysis. We focus on the determination of local structures of SACs via comparison between experiments and simulations, the discovery of distinctive catalytic mechanisms induced by multiadsorption, synergetic effects, and dynamic evolutions, to name a few, the proposal of criteria for theoretically designing SACs, and the extension of original concepts of single-atom catalysis. We hope that this Perspective will inspire more in-depth thinking on future theoretical studies of SACs.

KEYWORDS: single-atom catalysis, theoretical simulations, active sites, catalytic mechanisms, catalysts design



1. INTRODUCTION

While in homogeneous catalysis it has been known for a few decades that single-metal atoms can act as active centers, in heterogeneous catalysis, it is only in the last two decades that people began to prove and believe that isolated single-metal atoms could play a catalytic role.^{1–3} Since the concept of “single-atom catalysis” was formally proposed in 2011,⁴ much effort has been devoted to this area, promoting single-atom catalysis to become a new and highly active frontier in heterogeneous catalysis. These deposited isolated single atoms are expected to combine the respective advantages of homogeneous and heterogeneous catalysts, behaving as a conceptual bridge that connects both subfields. Compared with the constituent atoms in nanoparticles, the deposited single atoms are in a completely different bonding environment, as all other atoms connected with them are not of the same element. In addition, the electronic structures of the single atoms can be further tuned by adjacent bonding atoms⁵ via strong metal–support interaction (SMSI)⁶ or confinement.⁷ Using isolated single atoms as heterogeneous catalysts not only offers a novel way of maximizing the efficiency of utilizing atoms, but with the help of their surrounding environment, the single atoms can also exhibit distinct catalytic performance in various chemical reactions.

The dispersion of single atoms has been successfully realized on metal oxides, metals, carbon-based materials, metal–organic framework, and covalent-organic framework materials,^{8,9} and these anchored atoms have been widely employed to catalyze thermochemical, electrochemical, and photochemical

reactions.^{10–13} For thermo-catalytic reactions, SACs perform well on CO oxidation, CO₂ hydrogenation, hydroformylation reaction of propene, semihydrogenation of acetylene, and so on. As for electrocatalytic reactions, hydrogen evolution reaction (HER), oxygen evolution reaction (OER), oxygen reduction reaction (ORR), CO₂ reduction (CO₂RR), nitrogen reduction reaction (NRR), etc. have been intensively investigated in both experimental and theoretical works. SACs are also used for photocatalytic processes such as water splitting, nitrogen fixation, CO₂ reduction, etc. All of the reactions discussed in this work are summarized in Table 1.

Just like the confirmation of the existence of single-atom species cannot be achieved without the use of various advanced experimental characterization equipment, the revealing of the underlying mechanisms of single-atom catalysis cannot be accomplished without the information provided by theoretical simulations. Not only can the geometric configurations of the active sites be identified by the collaboration between theoretical simulations and experiments, but the detailed reaction processes can also be revealed by simulations at the atomic scale, from which the mechanisms could be extracted. The above-mentioned roles that theoretical simulations can

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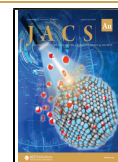


Table 1. Summary of the Applications of Different SACs Discussed in This Work

cat.	reactions	SACs
thermo-	CO oxidation	Fe ₁ (OH) ₂ /Pt; ¹⁸ Ir ₁ /Co ₃ O ₄ ; ³⁰ Au ₁ /h-BN; ³¹ Pd ₁ /graphene; ³² Co ₁ /MXene; ³³ Co ₁ /g-C ₃ N ₄ ; ³⁴ Pt ₁ /pentagraphene; ³⁵ Pt ₁ /CeO ₂ ; ⁶⁸ Au ₁ /TiO ₂ (CeO ₂) ^{69,70}
	CO ₂ hydrogenation	Pt ₁ /MIL-101; ¹⁹ Pt ₁ /MoS ₂ ⁵⁶
	hydroformylation	Rh ₁ /CoO ⁴⁵
	CH ₄ conversion	Fe ₁ /SiC ₂ ⁴⁶
	selective hydrogenation	Pd ₁ /Cu ^{48,49}
	water-gas shift	Rh ₁ /TiO ₂ ⁶⁷
electro-	HER	Co ₁ /g-C ₃ N ₄ ; ²⁵ Pt ₁ /MoS ₂ ; ⁵⁷ M ₁ -N _x C _y /C ¹⁷
	OER	M ₁ -N _x C _y /C; ¹⁷ Ru ₁ -N ₄ /g-C ₃ N ₄ ; ²⁶ Ni ₁ -pyridinic-N ₄ /C ⁴⁴
	ORR	M ₁ -N _x C _y /C; ¹⁷ Fe ₁ -N/C; ^{37,38,78} Fe ₁ -pyridinic-N ₄ /C; ³⁰ Fe ₁ /C ₂ N; ¹⁰³ Co ₁ -N ₂ O ₂ /C; ⁴² Ni ₁ -N ₄ /C ⁹⁰
	NRR	Cr ₁ (Mo ₁ , Re ₁)-N ₃ /C; ^{29,36} Fe ₁ /MoS ₂ ; ⁴³ Mo ₁ -N/C; ⁶¹ M ₁ /g-C ₃ N ₄ ; ⁸⁰ B ₁ /graphene(h-MoS ₂) ¹¹³
	CO ₂ RR	Co ₁ -N ₅ /C; ³⁹ Ni ₁ -N/C; ^{22,41,71,72} Cu ₁ /g-C ₃ N ₄ ; ⁴⁷ Cu-N ₂ ; ⁵⁸ Ni-N ₃ C ₁ (N ₂ C ₂ , N ₄)/C; ^{20,23} Cu(Ni, Fe, Mn, Co, In, Sn, Sb) ₁ -N ₄ /C; ^{79,96–98} Co ₁ -TAP ¹⁰²
photo-	water splitting	Co ₁ -phosphide/P-g-C ₃ N ₄ ; ²⁴ Pt ₁ /g-C ₃ N ₄ ; ²⁷ Cu ₁ /TiO ₂ ¹⁰⁵
	CO ₂ RR	Pt ₁ (Pd ₁)/g-C ₃ N ₄ ⁶⁴
	NRR	B ₁ /g-C ₃ N ₄ ; ¹¹¹ B ₁ /g-CN ¹¹²
	ORR	Si ₁ /g-C ₆ N ₆ ¹¹⁴

play are particularly prominent in single-atom catalysis. Generally, the structural inhomogeneity of catalysts brings about obstacles in determining the geometries of the true active sites and in establishing the corresponding structure–activity relations. Such inhomogeneity, however, is alleviated in single-atom systems, making SACs an ideal platform for the cooperation of simulations and experiments. Nevertheless, there can still be many variations in the local environment around the single atoms, and such changes may have significant impacts on their catalytic performance. Pragmatically, the ultimate goal of understanding reaction mechanisms is to use the obtained fundamental knowledge to design excellent catalysts. High-throughput computations based on first-principles simulations can thereby be used to screen out SACs with desirable properties and thus provide key guidance for the conduct of experimental works. For example, the approach of catalyst design, which is based on certain screening criteria, could be more efficient than the commonly used trial-and-error method. The essential roles of the theoretical simulations have been well presented in the investigations of SACs.

With the explosive growth of the corresponding research, single-atom catalysis has become a particularly active field in heterogeneous catalysis. Many excellent reviews have been published in recent years, overviewing the rapid development of this field from different viewpoints such as the chemical synthesis of SACs,⁸ the surface coordination chemistry of atomically dispersed catalysts,⁹ the microenvironment modulation of SACs,⁵ the full elemental diversity of SACs across the periodic table,¹⁴ the single atom alloy catalysts,¹⁵ and the applications of SACs in different types of reactions,^{5,6,9–13} to name a few. In terms of theoretical simulations, Gong et al. and Li et al. have given outstanding reviews on the diverse applications and properties of SACs¹⁶ and the stability and catalytic performance of graphene-based SACs,¹⁷ respectively. All these papers provide insightful summaries and enlightening comments for a comprehensive and profound understanding of both the state-of-the-art and future development of single-atom catalysis.

In this paper, we are committed to interpreting the theoretical simulations of SACs from a different perspective. Here, we do not focus on a specific type of reactions but,

instead, try to refine new concepts and mechanisms from the great theoretical achievements in active-site determination, reaction processes, dynamic evolutions, and material design of SACs. The possible limitations and controversial issues of current simulations of SACs are also mentioned. We hope that this Perspective will inspire new thinking and help guide future research efforts on the theoretical investigations on SACs. The remainder of this Perspective is organized as follows. In section 2, we discuss the determination of local structures of SACs. In section 3, we present a few new mechanisms of SACs, such as multiple adsorptions, synergistic effects, and dynamical processes. Section 4 provides the current stage and our thinking on the design criteria for desired SACs. Some developments involving new concepts of SAC are mentioned in section 5. We conclude with an outlook in section 6.

2. DETERMINATION OF LOCAL STRUCTURES

The local structure of a SAC usually has an important impact on its electronic structure and catalytic performance. Such information, unfortunately, is very difficult to fully obtain merely from experiments. For example, it is challenging to distinguish the elements of the coordinating atoms in the same period (like C, N, O). In addition, the detailed structural feature of the coordinated atoms/groups, such as whether it is O, OH, or OH₂, for instance, is also hard to identify at the current stage. The situation becomes more complicated when one considers that the local structure of a SAC is likely to change during the reaction process. Through the proposal of possible structural models combined with electronic (magnetic) structure analysis and spectroscopy simulations, theoretical calculations can provide plenty of information for comparison with experimental measurements, helping to shed light on the real structural characterization of SACs.⁸

Four typical types of coordination configurations present in single-atom catalysts are shown in Figure 1a–d. Isolated Fe single atoms were deposited on Pt nanoparticles, exhibiting high performance toward preferential oxidation of CO in H₂ (PROX).¹⁸ Under room-temperature PROX conditions, the fitting of an extended X-ray absorption fine structure (EXAFS) indicated that one Fe single atom forms three Fe–O bonds with bond lengths of 1.96, 1.96, and 2.01 Å, respectively. If the Fe atom is saturated by surface *O, the Fe–O bond lengths

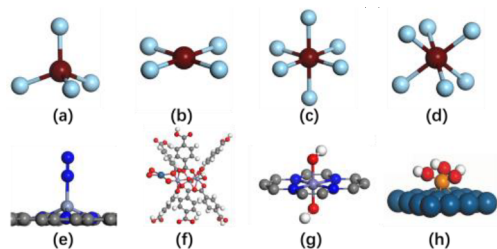


Figure 1. Schemes for four typical types of coordination configurations present in single-atom catalysts: tetrahedral coordinated (a), planar 4-fold coordinated (b), octahedral coordinated, (c,d) transition-metal atoms with different substrate coordination numbers and corresponding real structures, (e) one nitrogen molecule adsorption on three N doped graphene supported Cr single atom, (f) MIL-101 supported Pt single atom, (g) two hydroxyls saturated on both sides of Fe–N₄, (h) hydroxyl-coordinated Fe single atom supported by Pt nanoparticles. Adapted with permission from ref 18. Copyright 2019 Springer Nature.

would be much shorter than the fitting results based on theoretical modeling. By varying the ligand species, the structure of the active site was finally determined as Fe₁(OH)₃@Pt (100) with three Pt–O bonds of 1.93, 1.94, and 2.00 Å as shown in Figure 1h, which gives the best agreement between theoretical modeling and experimental observations. Except for the bond length and coordination number, the oxidation state of the single-metal atom is also a physical quantity that can be touched by theoretical simulations. For example, the local chemical environment of a Pt single atom in prepared Pt₁@MIL-101 was determined to be coordinated by two oxygens of the MIL-101 framework and one oxygen molecule, as shown in Figure 1f, which makes the Pt₁ species present as Pt²⁺ by charge analysis compared with Pt=O cluster.¹⁹ Thus, theoretical calculations can help to assert the accurate chemical state of coordination atoms, rendering them as powerful tools to determine the local structures of real SACs.

Single metal atoms supported by N-doped carbon-based materials (M–N–C) are the most intensively investigated SACs for their potential application in many reactions such as oxygen evolution reaction (OER), oxygen reduction reaction (ORR), hydrogen evolution reaction (HER), electrocatalytic nitrogen reduction reaction (eNRR), CO₂ reduction reaction (CO₂RR) and so on.¹⁷ However, the exact chemical environments of single atoms are difficult to be determined by EXAFS for the coexistence of the pyridinic nitrogen, pyrrolic nitrogen, carbon atoms in the substrates.^{20,21} Thus, a series of structures need to be constructed for comparisons with the experimental geometric/electronic structures and even catalytic performance. This could help to resolve the real structure of the active site such as in the detailed simulations of the CO₂ electroreduction kinetics on different Ni–N–C local structure.^{22,23} It should be noted that mixtures of single atoms with different microenvironments may coexist and contribute to the overall activity. X-ray photoemission spectroscopy (XPS) is a powerful tool to determine the local chemical structure of a specific element in experimental characterizations. The core level shift (CLS) simulations of N 1s and C 1s were performed by Hossain et al., trying to distinguish the local structure of Ni–N–C catalysts. Unfortunately, the differences in CLS for various N atoms are too small to be resolved by current spectroscopy.²² If the single metal is coordinated with elements in a different period such as Co₁–

phosphide anchored on phosphorus-doped graphitic carbon nitrides (PCN),²⁴ it will be accessible to determine the chemical environment of the Co-coordinated P atoms. EXAFS suggested that Co is surrounded by about four P atoms, and no P–P bond is formed. Two main peaks at 133.1 and 129.5 eV in the P 2p XPS spectra, as shown in Figure 2a, were, respectively,

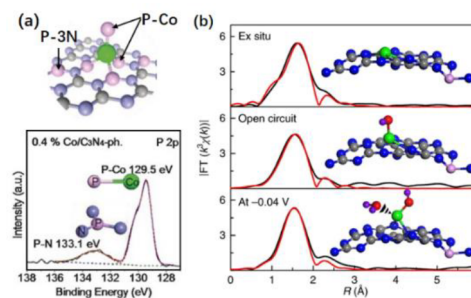


Figure 2. (a) Binding energy of P 2p in 0.4% Co/C₃N₄-ph and the schematic configuration of the assignment of the two peaks; (b) first-shell fitting of EXAFS spectra and the corresponding geometric configurations of Co₁–N₂ on g-C₃N₄ at different conditions. Adapted with permission from refs 24 and 25. Copyright 2017 Wiley-VCH and 2019 Springer Nature, respectively.

assigned to the P atom connected with three nitrogen atoms (P–N) in a C₃N₄ framework and that connected with the Co atom (P–Co). However, the chemical environments of P(–Co) is unclear, while the binding energy difference of P in different chemical environments could give an opportunity for more structural information on the Co–P center. It is expected that the theoretical CLS calculations based on constructed structures combined with stability evaluation may help to determine the real structure of atomically dispersed Co–P. With the enhancement of experimental binding energy resolution, CLS calculation may play more important roles in distinguishing the fine structures of SACs.

Except for the characterization of prepared SACs, the real structure under the reaction conditions is more important for the understanding of catalytic performance, but its determination remains a big challenge. Nowadays, with the development of the in situ/operando characterization techniques, more and more structures under working conditions are determined. For example, a highly oxidized HO–Co₁–N₂ moiety on graphitic carbon nitrides (g-C₃N₄) at open circuit was revealed via operando XAS, and H₂O–(OH–Co₁–N₂) was determined as the dominant species at –0.4 V during alkaline HER as shown in Figure 2b.²⁵ In addition, the configuration of the Ru₁–N₄ site anchored in carbon nitride was revealed to be O–Ru₁–N₄ under alkaline HER.²⁶ Theoretical works verified that the presence of extra species such as *OH or *O can improve the catalytic performance by lowering the overpotential. A new free Pt⁰ state of Pt₁ supported by g-C₃N₄ was also verified by the Pt–N bond breaking and the C=N bond reconstruction, as characterized by XPS during the photocatalytic water splitting reaction.²⁷ Operando EXAFS also showed the reduction of the coordination number of the Pt₁ atom supported on a nitrogen–carbon substrate during the alkaline electrochemical process,²⁸ which identified a dynamic near-free state of single atom. The evolution of the oxidation state of single-metal atoms under reaction conditions shows the complexity of single-atom catalytic processes, bringing challenges for theoretical simulations such as in the

construction of new structures or the simulations of reactions under excited states.

3. NEW CATALYTIC MECHANISMS

Just as a single atom cannot be simply treated as the size reduction of nanoparticles, the reaction processes and the underlying mechanisms involving single-atom catalysts should not be regarded as a simple repetition of those occurring on catalysts at the nanoscales. Acting as a bridge between the homogeneous and the heterogeneous catalysis, SACs provide an ideal platform for exploring and discovering new catalytic mechanisms. The highly coordinated unsaturation of SACs makes the adsorption of multiple reactants and/or intermediates possible. The SACs can also play a synergistic role in catalytic processes with its surrounding environment, including but not limited to adjacent atoms and nearby single atoms. Moreover, the dynamic evolution of the structural and electronic properties of SACs, especially those under realistic reaction conditions, may open new reaction channels that show lower energy barriers than imagined. Besides, a kinetic analysis of the entire reaction network also adds a new dimension to understanding the reaction mechanisms of the SACs. The above contents will be briefly discussed in this section.

3.1. Multiadsorption and Ligand

Single transition-metal atoms prefer to form tetrahedral, planar 4-fold, or octahedral coordination. If the supported/embedded single-metal atom is less coordinated, a different number of ligands may adsorb to saturate the coordination. For example, one nitrogen atom saturated 3-fold coordinated Cr_1 on pyrrolic nitrogen-doped graphene to form tetrahedral coordination (Figure 1e),²⁹ two CO molecules saturated 2-fold coordinated Ir_1 on Co_3O_4 to form planar 4-fold coordination (Figure 1b), one CO molecule saturated 5-fold coordinated Ir_1 on Co_3O_4 to form octahedral coordination (Figure 1c),³⁰ and three hydroxyls saturated 3-fold coordinated Fe_1 on Pt (Figure 1h).¹⁸ The multiadsorption of reactants may open new reaction pathways.

For the CO oxidation reaction on SACs, traditionally, the reaction proceeds via the Langmuir–Hinshelwood (LH) mechanism starting from coadsorbed CO and O_2 or via the Eley–Rideal (ER) mechanism starting from adsorbed CO (or O_2) with gas phase O_2 (or CO). However, on some SACs, multiadsorption of one reactant is energetically more favorable and new reaction mechanisms induced by the multiadsorption should be explored. On Au/*h*-BN, it was suggested that the coadsorption of two CO molecules as shown in Figure 3a opens a trimolecular ER reaction (TER) pathway via a newly proposed intermediate OCOOCO , which is approximately 5 orders faster than the traditional bimolecular LH mechanism

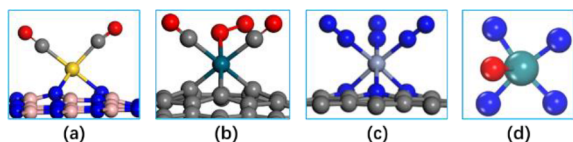


Figure 3. Multiadsorption configurations of two CO on Au/*h*-BN (a), two CO and one O_2 on Pd/graphene (b), three nitrogen molecules on $\text{Cr}_1/\text{N}_3\text{-G}$ (c), and oxygen-liganded Ru-N_4 on $\text{g-C}_3\text{N}_4$ at applied potential (d). Adapted with permission from ref 26. Copyright 2019 Springer Nature.

according to the microkinetics analysis.³¹ Now, the trimolecular reaction pathway has become a standard pathway for CO oxidation on supported SACs, such as Pd_1 supported on graphene ($\text{Pd}_1/\text{graphene}$),³² Co_1 supported on MXene³³ and $\text{g-C}_3\text{N}_4$,³⁴ and Pt_1 supported on pentagraphene.³⁵ On $\text{Pd}_1/\text{graphene}$, the revised LH (*r*-LH) mechanism was proposed based on the coadsorption of two CO and one O_2 as shown in Figure 3b.³² It was suggested that the second CO molecule reacts as a spectator during the formation of OCO by the combination of another CO and O_2 .

Besides the direct involving of reactions, the multiadsorbed species can also play as spectators but greatly impact the whole reaction performance. As for the eNRR mechanism on SACs, usually one adsorbed nitrogen molecule with either end-on or side-on is considered. However, it was found that on some 3-fold-coordinated SACs two or three nitrogen molecules can be effectively captured and the multiadsorption of N_2 may alter the activity and selectivity toward eNRR.^{29,36} As suggested by Zhao et al., the multiadsorption of three nitrogen molecules on 3-fold coordinated Cr_1 (Mo_1 , Re_1) supported by pyridinic nitrogen-doped graphene ($\text{N}_3\text{-G}$), as shown in Figure 3c, greatly inhibited the adsorption of $^*\text{H}$ on these SACs and enhanced the ammonia selectivity. Thus, the coadsorption modes of the reaction-related species under the working conditions should be carefully considered in the investigation of reaction mechanisms.

Except for interactions between single metal atoms and reactant molecules, the ligand of environmental species or intermediates is also important for the reactions. For example, the active site of the PROX reaction on Fe_1 anchored on Pt nanoparticles was verified as having a Fe_1 ligand by three hydroxyl groups as shown in Figure 1h.¹⁸ For two-dimensional materials embedded single-metal atoms, such as M-N-C , the metal atoms locate at the same plane of the nanosheet and the adsorption of related species on both sides also need to be considered. It was suggested that the catalytic performance of ORR on Fe-N-C is enhanced as the presence of the axial coordination such as $^*\text{OH}$ or $^*\text{O}_2$ on the other side of the nanosheet like the structure shown in Figure 1g.^{37,38} The Co-N_5 active center created by forming the fifth nitrogen coordination from the substrate was also designed to enhance the performance of CO_2RR .³⁹ On $\text{g-C}_3\text{N}_4$ anchored Co or Ru with a planar coordination, for the relative weak interaction between the single atom and the substrate, the single-metal atom was suggested to be pulled toward to one side of $\text{g-C}_3\text{N}_4$ with the accommodation of extra hydroxyl on $\text{Co}_1\text{-N}_2$ under alkaline HER²⁵ and extra oxygen on $\text{Ru}_1\text{-N}_4$ under acid OER²⁶ as shown in Figure 3d. Theoretical works suggested that the presence of hydroxyl on $\text{Co}_1\text{-N}_2$ enhances alkaline HER performance by improving the adsorption of water and lowering the dissociation barrier of water compared with the Pt (111) surface, and the ligand of extra $^*\text{O}$ on $\text{Ru}_1\text{-N}_4$ lowers the limiting potential of OER.²⁶ Thus, the multiadsorption and ligand with different configurations on one or two side of planar SACs should be carefully evaluated to try to get accurate descriptions of the reaction processes.

3.2. Synergetic Effects

The interaction between single-metal atoms and substrates can tune the catalytic performance from different aspects, such as electronic structure, spatial coordination, etc. The synergy between the single atom and substrates makes central metal atoms, central metal atoms combined with neighboring

coordinated atoms, or only the coordinated atoms act as the active sites for the catalytic processes as shown in Figure 4,

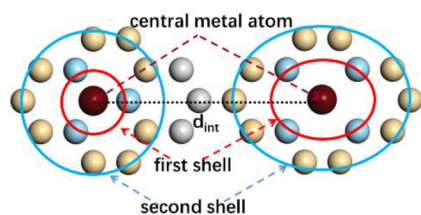


Figure 4. Scheme of the central single-metal atoms with their first shell and second shell coordination. d_{int} indicates the distance between two central single atoms.

which demonstrates that a careful investigation of the active sites is quite necessary. Furthermore, the dynamic evolution of the geometric or electronic structures provides some new pictures regarding reactions on SACs.

3.2.1. Central Single-Metal Atoms as Active Sites.

Usually, central single-metal atoms are considered as the active sites and their catalytic performances could be tuned by the corresponding coordination environments. For example, the electronic states of the Pt 5d orbitals were tailored by different substrates including oxidized graphene, CeO_2 , TiO_2 , and Co_3O_4 , with Co_3O_4 being the best one to achieve both high stability and a high hydrogen production rate via ammonia borane hydrolysis.⁴⁰ Theoretical works also indicated that on Ni–N–C the activity toward CO_2RR changes with the variation of the coordination elements (N, C) such as Ni– N_4 , Ni– N_3C , Ni– N_2C_2 , Ni– N_1C_3 , Ni– C_4 and so on.^{22,41} Such uncertainty of the coordination brings challenges for the understanding of the reaction mechanisms.

3.2.2. Neighboring Atoms as Active Sites. Except for central single-metal atoms, neighboring atoms can also participate in reactions as the active sites. For example, except for the central Fe atoms on Fe–pyrrolic–N–C, the carbon atoms of the second coordination shell, as shown in Figure 4, were also suggested to be the active sites for the $4e^-$ ORR process, bringing about an increase of the active site number and an enhancement of the ORR catalytic performance.³⁰ Moreover, the presence of neighboring atoms can also affect the selectivity. On Co–N–C, for example, if Co was coordinated with four pyridinic nitrogen atoms in the first shell, the Co site is the active center for ORR and the dominant product is H_2O . However, if the coordinated atoms in the first coordination shell were partially replaced by O atoms, such as Co– N_2O_2 , the active center was found to shift to the O-adjacent carbon atoms and H_2O_2 becomes the preferred product.⁴² Recently, in the investigation of the eNRR mechanism on Fe-decorated MoS_2 nanosheets, it was found that the active site is the Mo atoms along the Mo-edge of MoS_2 , rather than the deposited Fe single atoms. Nevertheless, the doping of the isolated Fe atoms can synergistically tune the eNRR activity and the selectivity toward ammonia.⁴³ Thus, for a comprehensive consideration of the reaction mechanisms, more possible sites should be taken into account instead of merely considering the central single-metal atoms.

3.2.3. Single Atom Center and Neighboring Atoms as Active Sites. Both the central single atoms and the surrounding sites can synergistically play the catalytic role as the active sites. For example, a dual-site mechanism was proposed for the OER process on Ni–pyridinic– N_4 .⁴⁴ Here,

*OH and *O prefer to adsorb on the second neighboring C atom, whereas *OOH and *OO are formed on the central Ni atom. The Ni atom and the second-coordinated C atom synergistically accomplished the OER process. Such the change in the adsorption sites lowers the required limiting-potential. However, the active site migration during the formation of *OOH at carbon site from the *O at the Ni site is expected to conquer an energy barrier, and the effect of the migration step on the whole OER rate is unknown now. Detailed kinetic investigations may be necessary to achieve a reasonable comparison between the one-site and dual-site reaction pathways rather than simply comparing the limiting-potentials. For more complicated reactions, the central metal atoms and neighboring atoms can bind with different surface species, which will be combined later in the reactions. For example, during the hydroformylation reaction of propene on Rh_1/CoO , it was found that propene and CO are captured by Rh_1 and the neighboring oxygen atoms of CoO provide adsorption sites for hydrogen atoms.⁴⁵ This coadsorbed configuration is essential to the selectivity of the reaction. As for the nonoxidative conversion of methane occurring on single iron atoms at silica matrix (Fe_1/SiC_2), a quasi-Mars–van Krevelen (quasi-MvK) mechanism that includes the extracting and refilling of Fe-coordinated C atoms was revealed for the formation of ethene.⁴⁶ During the production of ethanol from CO_2 electroreduction on $\text{Cu}_1/\text{g-C}_3\text{N}_4$, the C–C coupling was found to proceed between * CH_2OH on Cu and * OCH_3 on a neighboring carbon site.⁴⁷ The coadsorption configurations and also the diffusion processes need to be carefully investigated.

Single-atom alloy catalysts, in which one type of metal atoms are atomically dispersed on the surface of a different and often relatively inert metal, can break the scaling relations between transition-state energies and adsorption energies, thanks to a separation of two reaction centers.¹⁵ With the doping of a very small amount of Pd atoms onto the Cu (111) surface, Sykes et al. achieved both facile dissociation of H_2 at dispersed Pd atoms and weak adsorption of hydrogenation products on Cu (111) in one system.⁴⁸ Through theoretical simulations, it was found that a very small amount of Pd atoms in the subsurface layer can effectively reduce the energy barrier of H_2 dissociation at isolated surface Pd atoms, which could be employed to tune the activity of the single atoms.⁴⁹ It was predicted that replacing Pd with Pt atom may bring about a more efficient single atom alloy for selective hydrogenations.⁵⁰ The design strategy has also been used to expand the potential application in other reactions related to CO, H_2 , CH_4 , NH_3 , CH_3OH , and CO_2 .^{51,52} Here, screening based on theoretical simulations and verification by experiments are tightly integrated. In this way, a single-atom alloy catalyst for propane dehydrogenation was recently proposed and verified.⁵³ Except for the hydrogenation and dehydrogenation, the single-atom alloy catalysts have been found to exhibit other unique performance, such as inhibiting the coke formation in C–H bond activation⁵⁴ and tackling CO poisoning on Pt catalysts.⁵⁵

Thus, different pathways evolving various active sites need to be carefully considered in the investigation of catalytic mechanisms, especially for complicated reactions. Besides, the design of SACs by utilizing the synergetic effects between central metal atoms and neighboring atoms may be interesting for further exploration.

3.2.4. Neighboring Single Atoms as Active Sites. With an increase of the atom loading, synergetic effects between

neighboring single atoms may play an important role in the catalytic performance of SACs.⁵⁶ For example, on MoS₂, the neighboring Pt monomer sites could be present and work together with the increasing of Pt loading. Theoretical works unraveled that the active sites are the surface S atoms directly connected with Pt.⁵⁷ For the case of an isolated Pt monomer, the CO₂ hydrogenation proceeds via the following pathway: CO₂ → COOH → COHOH → CH(OH)₂ → CHOH → CH₂OH → CH₃OH, while for two neighboring Pt monomers, CO₂ prefers to be first hydrogenated to formic acid and then hydrogenated to methanol with the presence of enough hydrogen providing. The special configurations of –S–COOH and –S–H on the two neighboring Pt monomers shifts the attacking spot of –S–H from the oxygen atom in carbonyl to the carbon atom owing to the different weak hydrogen interactions.⁵⁶ Similarly, it was suggested that the presence of two adjacent Cu–N₂ sites synergistically leads to the C–C coupling and the production of C₂H₄ in the electroreduction of CO₂.⁵⁸ Two closely neighboring single atoms are also responsible for the promoting of the CO₂RR activity.^{59,60} Recently, two Mo–N–C sites about 6 Å apart were proposed to be active for eNRR through an alternative associative mechanism starting from a bridge-on adsorbed N₂.⁶¹ The synergetic interaction between the two neighboring single atoms breaks the conventional concept of isolated single atom and opens a new strategy to tune the catalytic properties. With the continuous advancement of the precise synthesis techniques, theoretical prediction may provide key guidelines for designing new neighboring SACs.

Except for the direct involving of two neighboring sites, the long-range electronic coupling between two single atoms at a long distance may also be used to tune the catalytic performance. It was found that with the continuous adsorption of up to four CO molecules on two FeN₃ site at a distance (*d*_{int}) of 11.40 Å within graphene, as shown in Figure 4, the magnetic state of the two FeN₃ sites varies from the ferromagnetic (FM) to the ferrimagnetic, the antiferromagnetic (AFM), the ferrimagnetic, and finally the AFM state, illustrating the synergetic intersite coupling via the graphene matrix.⁶² It was noticed that the adsorption energy of CO also changes, and it is expected that via the intersite synergetic effect the catalytic performance could also be tuned by the density of the single atom sites. In a fresh new work, it was suggested that the magnetic state of Fe–N₄–C and the adsorption free energy of *OH on it vary remarkably with the distance between two Fe–N₄–C sites decreasing from 5.0 to 0.5 nm, which greatly affects the ORR activity.⁶³ These works demonstrate the importance of the indirect intersite coupling, and the previous models with fixed *d*_{int} may have some limitations specially for anchored magnetic metal atoms. The intersite distance may be treated as a new dimension in the tuning of the catalytic properties of SACs.

3.2.5. Combining Single Atoms with Photoactive Substrates. In catalytic processes, single atoms can also cooperate with photoactive substrates. Single-atom photocatalysts can thus be designed and prepared by depositing isolated metal monoatoms on light-absorbing materials. Here, the electronic properties of the single atoms can be tailored by the interactions with the substrates, which may bring about enhanced abilities to adsorb and activate reactants. Meanwhile, the single atoms could also modify the band structures of the substrates for better light absorption.¹¹ One example is the g-C₃N₄ supported Pd/Pt SAC, which can be used as an efficient

photocatalyst for visible-light CO₂ reduction.⁶⁴ It was later predicted that hybrid perovskites, the emerging candidates in solar-cell applications, could be promising substrates for SACs.⁶⁵ First-principles simulations revealed that single Pt atoms can be stabilized on such substrates through a synergistic cooperation between covalent bond formation and charge transfer. The good catalytic properties of the loaded Pt SACs were also demonstrated by using CO oxidation as an exemplary reaction. Very recently, it was experimentally verified that perovskite-supported Pt single-atoms can indeed be used as efficient and durable photocatalysts for the semihydrogenation of propyne.⁶⁶

3.3. Geometric and Electronic Dynamic of SACs

In the theoretical simulations of SACs, static descriptions are often adopted on the behavior of single-atoms, which assumes, usually for simplification, that a single-atom would locate at a specific anchoring site and exhibits a fixed charge state. Although such an interpretation works well in many cases, several investigations have demonstrated that the assignment of a static location and a well-defined oxidation state for the single-atom catalyst is oversimplified.

One example is the Rh single-atom catalyst, in which single Ru atom dynamically adapts its location and coordination on rutile TiO₂(110) in response to redox conditions.⁶⁷ Under the presence of O₂, the Rh single atom prefers to localize at a 6-fold Ti site in the surface plain by way of substitution. This bonding pattern of Rh, which is favored during the catalyst synthesis process, is not catalytically active in the reverse water–gas shift reaction (RWGS). In the mixed atmosphere of CO and H₂, by contrast, the Rh single-atom changes its configuration from the substitution pattern to a surface-supported one, which is well stabilized by the CO adsorbates. It is the new structure of Rh that is responsible for the reactivity of the single-atom catalyst toward RWGS.⁶⁷ Another example is related to single Rh atoms supported on CoO (Rh/CoO).⁴⁵ During the hydroformylation reaction of propene, it was found that H₂ dissociates at the Rh atom to form two neighboring hydroxyl groups and thereby, weakens the interaction of Rh with the CoO substrate. Then the CO reactant pulls the Rh to the supported sites as shown in Figure 5a and makes it adaptive for the subsequent propene

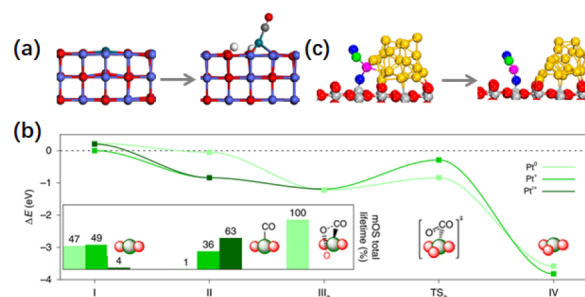


Figure 5. Geometric and electronic dynamics of SACs. (a) Shift of Rh atom from the embedded site to supported site on CoO with the interaction of reactants hydrogen and CO. (b) Reaction profiles of CO oxidation for each oxidation state of Pt on CeO₂ and the metal oxidation states (mOS) lifetimes of the reaction intermediates. Adapted with permission from ref 68. (c) Initial and final configurations for 2 ps of AIMD simulation at 700 K with one CO and one O_{ad} on metal oxide supported Au nanoparticle. Adapted with permission from ref 70. Copyright 2019 Springer Nature and 2016 American Chemical Society, respectively.

adsorption. The favorable coadsorption configuration of H₂, CO and propene as well as the lowered reaction energy barrier lead to the production of the linear product butyraldehyde.⁴⁵ The insight that single atoms can respond to the reaction conditions and adapt their coordination from inactive to active ones will shed new light on the exploration of the true active sites in catalytic reactions.

Except for the spatial position, charge state is a new dimension of SACs. A dynamic charge transfer is found to take place between Pt single atoms and the CeO₂ (100) substrate, making several interconnected charge states of Pt coexist.⁶⁸ This process stems from a phonon-assisted fluctuation of the Ce(4f) level positions relative to those of the Pt single atom, where a lowering of the Ce(4f) levels allows electron transfer from higher Pt-filled states and vice versa. The dynamic interchanges of the Pt charge state are closely related to the reactivity of the Pt single-atom catalyst toward CO oxidation. Here, the neutral Pt⁰ state that corresponds to the low-barrier reaction channel of CO oxidation does not possess a high ability to trap the CO reactants as shown in Figure 5b, while this step can be well achieved by the ionic Pt⁺ species. Thus, the dynamic conversion between the ionic and the neutral states of the Pt single-atom makes both adsorption and oxidation of CO proceed in their respectively effective ways.⁶⁸ The distribution of different charge states present challenges for theoretical simulations to assign the charge state.

In the above examples, the single atoms exist all the time, no matter whether their locations or the charge states have been changing dynamically. In fact, even the formation of the single-atom active site can be a dynamic process as shown in Figure 5c.^{69,70} Based on the *ab initio* molecular dynamics simulations of oxide-supported Au nanoparticles with tens of atoms, Rousseau et al. revealed a dynamic single-atom catalytic mechanism.^{69,70} They find that in the presence of CO, an isolated Au atom can be directly pulled out of the entire nanoparticle by one CO adsorbate, forming a cationic Au⁺–CO species. The cationic species can react with lattice oxygen or one O₂ molecule adsorbed nearby, opening a dynamic single atom catalytic channel with low barriers for CO oxidation. Once the CO₂ product desorbs, the generated Au single atom will reintegrate into the nanoparticle, waiting to be generated again assisted by another CO adsorbate.^{69,70} This discovery reflects that the single-atom system being the reaction center can exist as a transient that appears and disappears in the actual reaction process. It is worth noting that the above dynamic picture can be hardly imagined from theoretical simulations that are merely based on a static interpretation, reflecting the limitation of the static picture in exploring the true active sites and reaction processes in single-atom catalysis.

3.4. Advanced Simulation Methods

The factors such as pressure, temperature, solvent, applied potential, charge effect, pH value, and so on are important aspects that influence reaction processes under real working conditions. To bridge theoretical simulations and experimental observations, advanced simulation methods such as thermodynamic analysis, molecular dynamic simulation, more accurate methods to simulate real working conditions, microkinetics analysis, calculations with high level accuracy, and so on are necessary to draw a comprehensive picture of reactions.

For the CO oxidation reaction, several reaction mechanisms have been proposed, such as the traditional LH, ER pathways, and the recently proposed revised LH(r-LH) and TER ones.

Also, the adsorption configurations of the reactants of CO and O₂ vary with the partial pressure and reaction temperature, and such variations can be evaluated by thermodynamic analysis by including contributions of zero-point energy and entropy. Moreover, to get the whole picture of the CO oxidation on SACs, a reaction network including all possible pathways needs to be constructed and analyzed via microkinetic analysis. For example, it is demonstrated that the r-LH pathway is the most accessible route for CO oxidation on monodispersed Pd atoms on graphene.³² Since the reaction pathways may vary with reaction conditions, a full reaction network based on all possible adsorption configurations should be carefully constructed, in order to gain accurate reaction kinetics for comparisons with experimental observations.

The electroreduction CO₂ to CO on Ni–N–C is one of the most intensively investigated electrocatalytic reactions.^{41,71,72} However, the real structure of the active sites, the appearance of the intermediate CO₂^{δ−},¹⁸ and the high selectivity toward CO rather than H₂ are long debating.⁴¹ Hossain et al. intensively investigated the CO₂ reduction and the HER mechanisms on Ni–N₃C₁, Ni–N₂C₂, and Ni–N₄ and built a strategy for simulating CO₂ reduction kinetics including the current density of CO or H₂ evolution versus the applied potential and the Tafel slope of CO₂ reduction.²⁰ The relationships between the faradic efficiency, the turnover frequency, and the Tafel slope for the CO and H₂ productions versus the applied potential (*U*) are determined by the grand canonical potential kinetics (GCP-K) formulation. The HER process is divided into the dissociation of water to form *H on Ni site and the formation of H₂ between *H and H₂O. With the consideration of the onset potential, the CO current, and the CO selectivity, Ni–N₄ is suggested to achieve both high current and high CO selectivity. However, it is noticed that the theoretical onset potential on the active sites is higher than the experimental measurement. In addition, only a slightly bent CO₂ configuration is suggested compared to the one induced by the electron transfer, which disagrees with the observation of CO₂^{δ−}. A few more coordination environments around the Ni single atom, including Ni–C₃, Ni–C₄, Ni–N₄, Ni–N₃C₁, Ni–N₂C₂, and Ni–NC₃, were constructed by Zhao et al. to investigate the CO₂ electroreduction performance.²³ With the inclusion of an explicit water solvent model and the surface charges, the adsorption of CO₂ is barrierless on Ni–C₃N and the energy barrier of the *COOH formation is lower than the formation of adsorbed *H from H₂O via the Volmer step, which gives an explanation of the observation of CO₂^{δ−} and the high selectivity toward CO. Based on the kinetic simulations, they pointed out that the hybrid coordination environment of Ni–C₃N is the active site with a relatively low energy barrier for the electrochemical steps, including the formation of *COOH and the production of *CO than that on other active sites. The high activity is assigned to the high capacity of Ni–NC₃ to adsorb and activate CO₂. The diversity of possible active sites should be intensively considered for their distinct catalytic performance and more advanced simulation methods, including but not limited to solvent effects, applied potentials, and charge states are required. The theoretical framework may be widely used to more systems like CO₂RR on Fe–N–C⁷³ and to other reactions.

At the current stage, most of the theoretical works are based on general gradient approximation functionals. However, for magnetic transition-metal atoms, calculations based on hybrid functionals may bring different reaction mechanisms. For

example, the Fe site embedded with different numbers of N and C including Fe–C₄, Fe–N₂C₂, Fe–N₃C, Fe–N₄, Fe–NC₂, and Fe–N₃ are predicted to be covered by CO on the basis of RPBE calculations. However, on the basis of HSE06, Fe–N₂C₂, Fe–N₃C, and Fe–N₄ are not covered by CO,⁷⁰ which alters the reaction kinetics of CO₂ electroreduction on Fe–N–C. Thus, the adoption of a more accurate exchange-correlation functional may play an important role in the understanding of single atom catalytic mechanisms. Furthermore, to deeply understand the photocatalytic processes beyond the photon-absorption and band structure alignment, the simulations of the dynamics of excited electrons or holes, the dynamics of structure evolution of SACs at excited states, and the subsequent surface reactions driven by hot electrons or holes are necessary but still difficult at the current stage, which requires further development of the simulation methods.

4. DESIGN CRITERIA

With the development of computational methods and the continuous expansion of computing capacities, high-throughput screening of catalysts via extensive computations emerges as a new frontier in theoretical catalysis, which is more efficient than the trial-and-error approach usually used in the laboratory. Such an approach has been employed for the rational design of desired SACs toward different reactions like HER, ORR, OER, eNRR, and CO₂RR, to name a few. In modern society, standards represent a formula that describes the best way of doing things. It is thus not surprising that the development of any field will be closely related to the establishment of the corresponding criteria. The desired SACs, like all catalysts, are also expected to possess satisfactory stability, excellent activity, and outstanding selectivity. Thus, it is highly urgent to call for reasonable, effective, and unified standards for evaluating the stability, activity, and selectivity of SACs. The criteria that have been proposed in these aspects will be reviewed and commented on in this section. Based on the design criteria, the exploration of key descriptors is becoming more and more significant for large-scale screening of new SACs as shown in Figure 6.

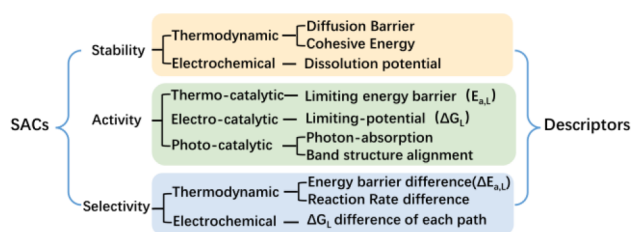


Figure 6. Scheme of the widely adopted evaluation criteria for the stability, activity, and selectivity of SACs.

4.1. Stability

The aggregation or leaking of single-metal atoms and the decomposition of substrates are related to the stability issues as shown in Figure 6. As for the thermodynamical stability, the negative formation energy of M₁/sub relative to isolated M₁ (E_b) or the cohesive energy of the metal bulk (E_f),^{74,75} the energy difference between the anchored sites and the neighboring sites are adopted to screen thermodynamically stable SACs.³⁶ Molecular dynamic simulations are always performed to verify the stability. The formation energy corresponding to the cohesive energy of each metal atom in

bulk is a strict standard for the stability evaluation because if single-metal atoms are deposited on the anchoring sites the aggregation process maybe kinetically controlled.

As SACs are widely used as electrocatalysts, it is quite necessary to discuss the electrochemical stability of SACs. To evaluate the possible dissolution of metal atoms, the dissolution potential defined as $U_{\text{diss}} = U_{\text{diss}}^0(\text{metal, bulk}) - E_f/eN_e$ is used to screen stable M₁/sub,⁷⁴ where $U_{\text{diss}}^0(\text{metal, bulk})$ is the standard dissolution potential of the corresponding bulk metal, E_f is the formation energy corresponding to the most stable bulk phase, and N_e is the number of electrons involved in the dissolution process.⁷⁶ Here, more positive U_{diss} values correspond to more stable SACs under electrocatalytic processes.⁷⁴ On the basis of the different dissolution of each cluster and dispersed single atoms, Liu et al. proposed an electrochemical potential window (ECPW) strategy to achieve a high-loading of Pt, Ni, or Pd single atoms or clusters.⁷⁷ It is noticed that the definition of U_{diss} originates from metallic states, but the anchored single-metal atoms would always be charged. Thus, more proper criteria are required to accurately assess the stability under positive potentials. Guo et al. predicted the dissolution potentials of a series of supported SAs, and the criterion of U_{diss} was widened to >0.0 V rather than the original >0.7 V, considering the uncertainties of the different numbers of the involved electrons between SACs and bulk materials.⁷⁴ Furthermore, the pH of the working conditions affect the dissolution of single-metal atoms. A DFT-accessible descriptor has been proposed by Holby et al. to evaluate the stability of Fe–N–C in ORR.⁷⁸ The dissolution potentials discussed above are under positive potential, but under negative potential it is possible to reduce the anchored metal atoms to metal clusters such as the transient formation of metallic copper nanoparticles responsible for the high ethanol selectivity for CO₂ electroreduction on Cu–N₄ embedded in the carbon matrix.⁷⁹ How to evaluate the electrochemical stability under negative working potentials has not been discussed yet.

Furthermore, the adsorption of reactants or intermediates will change the stability of SACs, and the assessment under specific reaction conditions is also desired. For example, the TiO₂-supported Rh₁ shifted from the original most stable five-coordinated substitution site to a supported site upon the adsorption of CO.⁶⁷ Under the electrochemical working conditions, with the influence of ligands or reaction related species, the relative stability of SAs within different coordination environments may change. Thus, the stability and the dissolution potentials may need further evaluation. Tremendous SACs have been designed for the CO₂ and N₂ electroreductions,^{29,36,80,81} but the stability of SACs under electroreduction conditions has not been intensively discussed.

Except for the dissolution of metal atoms, the loss of elements in substrates, such as nitrogen and carbon atoms in N-doped carbon materials, may lower the catalytic performance of the supported SACs. Liu et al. proposed a method to theoretically evaluate the decomposition potential (U_d) for an N-doped substrate during the eNRR reaction, at which point the nitrogen atom in the substrate is reduced to ammonia. The U_d is estimated as $-1/3$ of the free energy change in reaction $C_xN_y + 3(H^+ + e^-) \rightarrow C_xN_{y-1} + NH_3(g)$, which suggests that the limiting potential of eNRR should be more positive than U_d to ensure the stability of nitrogen in the substrate.⁸² Under the OER or ORR conditions, the carbon atoms in widely investigated Fe–N–C catalysts can be oxidized to CO or

CO₂.¹² Thus, according to the working conditions, criteria related to possible side reactions are expected to be provided to comprehensively evaluate the stability of SACs during the theoretical design of new SACs.

4.2. Activity

For stable SACs, high activity is always expected for specific reactions. Theoretical standards are adopted to screen SACs with high activity such as exhibiting low energy barriers in the rate-limiting steps of heterogeneous catalytic reactions^{30,56,83,84} or low reaction Gibbs free energies of the potential-limiting steps along electrocatalytic reactions. However, as discussed in section 3.4, to predict the catalytic activity of designed SACs, thorough considerations of various factors are necessary.

Many heterogeneous catalytic reactions, like CO oxidation,³¹ CO₂ hydrogenation,⁵⁶ selective hydrogenation of unsaturated bonds,^{13,83,84} direct methane oxidation to methanol,⁸⁵ and so on, have been intensively investigated. A series of elementary steps are constructed, and the transition states are determined to get the energy barriers for every elementary step. During the investigations, the possible multiadsorption and reconstruction under working conditions, and the different synergetic effects should be carefully considered to determine the most favorable reaction pathway. Thermodynamic calculations, MD simulations, and micro-kinetics analysis may play important roles in predicting the reaction activities and comparing them with existing experiments.

Different from describing the activities of SACs in electrochemical reactions, for which there are usually well-established descriptors from adsorption strengths, describing SACs' activities in thermochemical reactions seems more complicated and lacks a unified framework. This is partly because thermal catalysis involves different types of SACs and a wide range of reactions. For example, normally SACs deposited on reducible oxides are good thermocatalysts for oxidation reactions, while single-atom alloys are more suitable for catalyzing reactions under reducing conditions.⁸⁶ Anyway, charge, coordination number, and interactions with substrates will all affect the activities of SACs in thermal reactions. First-principles simulations combined with statistical learning⁸⁷ and artificial intelligence⁸⁸ have shown great advantages in describing the properties of thermal SACs and will play a more important role in future works.

Tremendous theoretical works have been performed to design new SACs and predict the potential activities toward HER, OER, ORR, eNRR, and CO₂RR by calculating the reaction Gibbs free energy for each of the elementary steps based on the computational hydrogen electrode method. For example, the adsorption Gibbs free energy of *H (ΔG_{*H}) compared with standard Pt(111) is used to predict the acid HER activity,⁵⁷ and the water dissociation barrier is used to evaluate the activity of the alkaline HER.²⁵ Usually, an excellent HER catalyst is expected to have a ΔG_{*H} close to zero or a low water dissociation barrier. Based on this criterion, a lot of SACs have been proposed, like Pt₁ doped MoS₂ as an example.^{57,86} The possible coadsorption of intermediates may be evaluated according to the working conditions such as the formation of the HO–Co₁–N₂ moiety on g-C₃N₄ under alkaline HER.²⁵ As for eNRR, the hydrogenation processes of one adsorbed nitrogen molecule with end-on or side-on mode is usually investigated to obtain the whole reaction Gibbs free diagram of the eNRR process and to determine the required

limiting potential of the whole reaction. In many works, SACs with lowest limiting-potential for eNRR starting from the side-on mode were screened as potential electrocatalysts for eNRR.⁸⁰ However, in many cases, this side-on adsorption geometry is less stable than the end-on structure, and an energy cost to convert the end-on mode to the side-on one is required, thereby lowering the reaction rate owing to the energy difference between two adsorption configurations. Furthermore, on several SACs, preferential multiadsorption of nitrogen molecules has been suggested.^{29,36} As for OER,¹⁰ the presence of *O are expected to lower the limiting potential on SACs such as on Ru₁–N₄ within carbon nitride²⁶ and the Ru₁ single atom supported by a PtCu alloy.⁸⁹ Similarly, during ORR processes, extra *OH or *O₂ were suggested to present on Fe–N–C depending on the reaction condition.^{37,38}

Thus, for low-coordinated single atoms, the multiadsorption of reactants or intermediates should be a common phenomenon during the catalytic process. To describe the activity of SACs, the coverages of both the reactants and the intermediates under working conditions should be carefully analyzed and properly taken into account. For example, to rationally design SACs with a high OER or ORR performance, the presence of possible intrinsic intermediates such as *O, *OH, or *O₂ should be kinetically analyzed and the corresponding effects on the catalytic performance should be discussed. It should be noted that for SACs embedded within planar two-dimensional materials, the possible binding of related species on both sides of the two-dimensional planes needs to be considered, as shown in Figure 1c. Furthermore, as discussed in section 3.4, kinetic simulations are necessary to well describe the activity of the CO₂ reduction on Ni–N–C. However, this approach is time-consuming, and methods with less computational costs are highly desired. Building proper criteria with high practicability to evaluate the catalytic activities is important for rational design of SACs.

4.3. Selectivity

Product selectivity is an important target of catalytic processes such as C₂H₄ selectivity during C₂H₂ hydrogenation, ammonia selectivity during the eNRR process, H₂O₂ selectivity during electroreduction of O₂, special C₁ or C₂₊ product during CO₂ electroreduction, and so on. Thus, criteria are required for properly evaluating the product selectivity of theoretical designed SACs.

For the semi-hydrogenation of acetylene, the lower desorption energy of ethylene relative to the energy barrier of the formation of *CH₂CH₃ is usually used to evaluate the C₂H₄ selectivity.^{83,84} As for the selective production of H₂O₂ by the reduction of oxygen, the free energy changes in the formation of H₂O₂ from *OOH and in the formation of *O are compared to screen the SACs for high H₂O₂ selectivity.⁷⁴ On Ni–N₄–C, however, the formation of *O is energetically more favorable than that of *H₂O₂, but H₂O₂ is still produced with high selectivity. It is assigned to the higher kinetic barrier in the formation of *O than that of H₂O₂.⁹⁰ Thus, the criterion of a lower free energy of *H₂O₂ may be too strict and mild criteria could be proposed for the screening of potential candidates for selective production of H₂O₂.

For the nitrogen electroreduction, the main side product is sometimes N₂H₄. Negative N₂H₄ adsorption free energy indicates a negligible production of N₂H₄.⁹¹ The preferential adsorption of molecular nitrogen rather than atomic hydrogen without or with applied potential⁹² or the less negative limiting

potential of eNRR compared to HER are adopted to screen SACs with high ammonia selectivity. However, it is noticed that for some supported low-coordinated single-metal atoms, upon the adsorption of one nitrogen molecule, the N_2 -coordinated metal atom becomes more active for HER, which makes $*N_2$ -SACs active for HER. Zhao et al. proposed that the competition between N_xH_y hydrogenation and the adsorption of $*H$ on M_1 sites with precovered nitrogen-containing species could be a new criterion for the evaluation of ammonia selectivity on SACs.³⁶ Thus, to theoretically evaluate the ammonia selectivity, possible multiadsorption may need to be carefully considered.

As for the CO_2 electroreduction, due to the diversity of the reduction products, it is difficult to control the product distribution, especially among the C_{2+} products.⁹³ The mechanisms of the selective production of CO or formate on SACs have been intensively investigated, and the main byproduct is H_2 .^{94,95} On atomically dispersed Ni (Fe, Mn, Co), CO_2 is selectively reduced to CO, while on In(Sn, Sb) the main product is formate. The lower reaction free energy in the formation of $HCOO^*$ (ΔG_{HCOO^*}) instead of $*COOH$ (ΔG_{*COOH}) makes formate be the main product on the $In^{\delta+}-N_4$ and $Sb-N_4$ interface sites.^{96,97} However, the higher ΔG_{HCOO^*} than ΔG_{*H} fails to describe the high selectivity of formate.⁹⁶ This discrepancy also appears in the discussion of CO production and HER.⁴¹ Thus, kinetic analysis should be included to explain the preferential production of the C_1 product and the inhibition of HER as discussed in section 3.4. Furthermore, if ΔG_{HCOO^*} is lower than ΔG_{*COOH} and the free energy of the potential-determining step for formate is higher than that of the formation of CO,⁹⁸ CO was suggested as the dominant product. However, the lower energy of $HCOO^*$ would make the active sites unavailable for $*COOH$, which may contradict previous discussion in the selectivity. And it is noticed that the calculated overpotential and selectivity between formic acid and CO on the same local structure of $In-N_4$ is contrary in two different works,^{96,98} which calls systematic works to clarify the confusion. Besides, the evaluation of the selectivities toward methanol, ethylene, ethanol, and acetic acid is also desired by proposing and employing new criteria.

4.4. Descriptors

Usually based on high-throughput computations, a descriptor can be found to describe the activity trend of a series of different catalysts, such as the widely used d-band center, the adsorption energy of important surface species such as $*O$, $*N$, or $*CO$,^{74,82,99} and so on. Recently, the dipole of adsorbed $N\equiv N$ was proposed as the descriptor for eNRR activity.¹⁰⁰ In this way, several new electrocatalysts with superior performance were successfully screened out. One possible limitation is that the descriptors are only suitable for describing specific electrocatalytic reactions. Moreover, it may not be so intuitive how to tune the adsorption free energies into the optimal ranges when one tries to optimize the performance of the electrocatalysts in experiments.

The work by Zeng et al. takes a remarkable step in designing and applying the concept of descriptors.⁹⁹ For different transition-metal single atoms embedded within (N-doped) graphene and for different electrochemical reactions (HER, OER, ORR), they proposed a universal descriptor that takes the local environment of the metal center into account. Here, the considered factors include the electronegativity and the

coordination number of the metal atom, as well as the electronegativity of its nearest neighboring atoms. This universal descriptor exhibits linear relations with the adsorption energies of different intermediates, and accordingly, can correlate with the activity of different electrochemical reactions. More interestingly, compared with the calculated adsorption free energies, the quantities involved in the descriptor are all numbers that can be directly tabulated without complicated computations or can be adjusted easily from intuition. Thus, this universal descriptor itself and the underlying idea in constructing the descriptor will play a more straightforward role in designing and screening single-atom electrocatalysts with outstanding performance.

With the development of machine-learning methods, the essential quantities such as metal types, coordinated elements, atomic radius, electronegativity, the number of valence electrons, coordination numbers, configurations, and maybe atomic orbitals¹⁰¹ can be involved to fit the descriptors correlated with activity or selectivity. A simple and intuitive form of descriptor would be powerful for designing SACs.

With the development of new simulation methods, the proposal of advanced machine learning strategy, and the adoption of more proper criteria for evaluating stability and catalytic performance under realistic working conditions, theoretical design is expected to play a more important role in promoting experimental works of SACs.

5. NEW CONCEPTS

The formal proposal of the concept "single-atom catalysis" comes from the brilliant experiment in which isolated nonmagnetic single-metal atoms of Pt were deposited and stabilized by the FeO_x substrate.⁴ In similar ways, isolated magnetic single atoms can also be anchored,^{62,63,102} with their spin polarization being a new degree of freedom in tuning the catalytic properties of the SACs. The concept of single-atom catalysis, naturally, can be further extended to nonmetal species. A common feature of all the examples is that, with the electronic structure of the SACs being regulated by the substrates, the isolated single atoms do not act in isolation but, instead, play a catalytic role with the substrates as a whole. Interestingly, deposited isolated single atoms can spontaneously exhibit similar behavior like free atoms in a completely isolated state, or, intendedly, be placed in absolute isolation and behave as completely different SACs. Furthermore, the concept of SACs can also be extended to single cluster catalysts and single superatom catalysts. The former breaks the limitation of using only one atom, and thus, more complex reactions can be catalyzed by employing a specific number of several atoms. In the latter case, it is intended to use multiple atoms to imitate the catalytic behavior of a single atom. The expansion of the original concept of SACs is of fundamental importance and may bring about new research paradigms and directions for single-atom catalysis.

5.1. Magnetic Single-Atom Catalyst

Spin is an intrinsic property of SACs. Modulating the spin states of materials can further affect their intrinsic properties such as magnetic and electronic structures.

Very recently, Gong et al. successfully fabricated the single Co atoms centered in porphyrin units of covalent organic frameworks (COFs), COF-367-Co.¹⁰² They found that by rationally regulating the oxidation states of single Co atoms such as Co^{II} -TAP and Co^{III} -TAP, as shown in Figure 7a, the

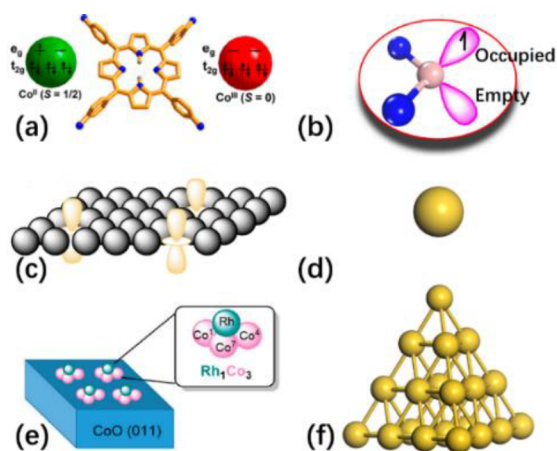


Figure 7. New concepts of single atom catalysts: (a) anchored magnetic single atom with different spin states, Co^{II} and Co^{III} ; (b) nonmetal boron in B/g- C_3N_4 with occupied and empty sp^3 orbitals; (c) free-d state in single atom alloy; (d) isolated atom; (e) scheme of dispersed single RhCo_3 cluster; (f) superatom Au_{20} . Adapted with permission from refs 102, 111, 115, and 120. Copyright 2020, American Chemical Society, 2018 American Chemical Society, 2019 Springer Nature, and 2019 American Chemical Society, respectively.

spin states of single Co atoms could be manipulated between a high spin state and a low spin state. Experimental and theoretical simulations indicate that Co^{III} -TAP with a high spin state is more active for the electroreduction CO_2 to HCOOH via the COOH pathway than Co^{II} -TAP with a low spin state. Zhong et al. reported the oxygen reduction reaction catalyzed by single iron atoms supported on C_2N , and they found a nearly linear relationship between the catalytic activity and spin moment variation.¹⁰³ The spin–activity correlation in a single Co atom supported by TaS_2 -catalyzed oxygen evolution reaction was also reported in a combined experimental and theoretical work.¹⁰⁴ By using *ab initio* nonadiabatic molecular dynamics simulations, Cheng et al. found the spin selection could enhance charge carrier lifetimes and thus boost the reaction in a photocatalytic water-splitting reaction catalyzed by single copper atoms on Anatase TiO_2 .¹⁰⁵ Both experiments and simulations have demonstrated that the rational modulating spin states of SACs is a promising method to boost the catalytic performance. It is expected that in future theoretical works different spin states achieved via tuning the electron numbers or coordination environments should be carefully considered rather than only considering the most stable configurations. What should be mentioned is that the functionals used for simulations could affect the relative stability of different spin states and the spin state may vary during the reaction process, which maybe important for spin catalysis.

5.2. Nonmetal Single-Atom Catalyst

In most cases, single-atom catalysts represent single-metal atoms anchored on supports. By rational design and the state-of-the-art synthesis strategies, nonmetal catalysts also exhibited excellent catalytic performance.^{106–108} On the one hand, nonmetal catalysts with lower cost can greatly reduce the consumption of metals; on the other hand, they might have higher corrosion resistance and antipoisoning ability than metal-based catalysts in some catalytic reactions.^{109,110}

Legare et al. found that boron atoms could serve as active sites in nitrogen reduction¹⁰⁸ because of the coexistence of

empty and occupied states to activate the $\text{N}\equiv\text{N}$ triple bond via accepting the lone-pair electrons from N_2 and back-donating electrons into the antibonding orbitals of N_2 , similar to the transition metals. Since then, several theoretical investigations focused on the utilization of nonmetal single boron atoms to catalyze the nitrogen reduction.^{111–113} One prime example is by doping single B atoms into graphitic carbon nitride (g- C_3N_4) for the photocatalytic nitrogen reduction reaction¹¹¹ as shown in Figure 7b. The single nonmetal B atoms can strongly adsorb and activate N_2 molecule. Next, Lv et al. found that a single B atom supported on holey g-CN (B@g-CN) can serve as a metal-free photocatalyst for highly efficient N_2 fixation and reduction under visible and even infrared spectra.¹¹² After screening of single boron atoms supported on 21 substrates, single boron atoms supported on graphene and substituted into h- MoS_2 were revealed as the most promising eNRR catalysts, and the catalytic activity of boron depended greatly on the degree of charge transfer between the boron atom and the substrate.¹¹³ Besides the intensively studied boron atoms, a single Si atom doped on the alternative pores of the porous graphitic carbon nitride (g- C_6N_6) surface was also found to be a potential and efficient catalyst in photocatalytic oxygen reduction reaction.¹¹⁴ This conceptual design research e.g., nonmetal single-atom catalyst, opens a promising avenue for single-atom catalysis.

5.3. Free d State and Isolated Single-Atom Catalyst

An unusual characteristic in the electronic structure appears in a single-atom alloy system. According to the experimentally measured valence photoemission spectra, the d state of isolated Cu atoms, which are embedded into a silver host at a very low concentration, shows a sharp peak close to the Fermi level, exhibiting a free-atom-like feature^{115,116} as shown in Figure 7c. It was experimentally verified that the dilute Pd dopant in the Ag host also shows similar free-atom-like peaks.¹¹⁷ Kitchin et al. revealed that the ineffective mixing of the electron densities between the host and the dopant atoms as well as an effective tensile strain is the reason for the emergence of such free-atom-like state.¹¹⁸ It is expected that such the unusual state could play a special role in catalytic processes. Further works need to be carried out to explore the potential of the emergent electronic feature of single-atom alloy.¹¹⁹

All of the above-discussed single atoms are supported by substrates, and the dispersed single metals usually act as active sites. A very recent combined experimental and first-principles theoretical investigation found that isolated single gold atoms within van der Waals complexes can serve as a catalyst in the absence of a surface as shown in Figure 7d.¹²⁰ This is observed in dissociative ion–molecule reactions of $[\text{diol-Au}]^+$ in superfluid helium nanodroplets. In contrast to isolated diol molecules, by introducing single atom into helium nanodroplets C_2H_4^+ ion becomes the sole prominent ionic product.¹²⁰ The catalytic effect is attributed to the softening of a remote C–O bond in diol molecules by these single gold atoms, which is also confirmed by density functional theory calculations. Since the formation of van der Waals complexes is ubiquitous, it may have wide chemical significance, e.g., as a new strategy for the design of catalysts that beyond the isolated single-atom catalyst.

5.4. Single Cluster Catalyst and Single Super-Atom Catalyst

Recently, the concept of single-atom catalysts was extended to the single cluster catalysts (SCCs), where singly dispersed

dimeric, trimeric, or multiatomic clusters serve as active sites that can exhibit distinctly different properties.^{77,121–124} For example, the Rh₁Co₃ (Figure 7e) SCC shows 100% selectivity for the reduction of NO to N₂, behaving much better than Rh–Co bimetallic nanoparticles.¹²¹ The cationic state of the active sites and a minimized number of reactants' binding configurations are responsible for the extraordinary catalytic performance.¹²¹ In the thermal ammonia synthesis, a Fe₃ SCC was found to open an associative mechanism for the N≡N bond cleavage.¹²⁴ Here, the Fe₃ site bypasses the constraint of the Brønsted–Evans–Polanyi relations via donating electrons at the adsorption steps while accepting electrons in the hydrogenations, and the large spin polarization of Fe₃ also helps the N₂ activation.¹²⁴ In some complex reactions, the SCCs can exhibit even better performance than the corresponding SACs.^{125,126} For example, in the epoxidation of *trans*-stilbene, the Fe₂ SCC shows much better catalytic performance than the Fe SAC.¹²⁵ Here, the highly unsaturated coordination of Fe₂ brings about a low dissociation barrier of the O₂ reactant, and the structural arrangement of the diatoms promotes the generation of the weakly bound single-coordinated oxygen atoms. In other words, at the Fe₂ site, the oxygen species exhibit both facile dissociation and weak adsorption at the same time. In addition, superatoms are a special type of clusters with an electronic structure as a single atom.¹²⁷ Interesting catalytic phenomena might be found for single superatom catalysts as shown in Figure 7f.

6. CONCLUSION AND OUTLOOK

Since the terminology of “single-atom catalysis” was formally proposed 10 years ago, rapid developments and great achievements have been continuously made in this area. Like digging a mine with endless treasures, exploring this field not only finds many catalysts with excellent performance but also deepens our understanding of catalytic concepts and mechanisms. Although the structure of the single-atom catalysts is somewhat simplified compared to the corresponding systems at the nanoscale, revealing the true active sites is still a challenging task. The local coordination of SACs can be affected by several factors like the reaction atmosphere, temperature, solvent, and pH, to name a few, and may exhibit significant changes during the reaction processes. Simulating the behaviors of SACs under operando conditions will greatly expand our exploration scope of single-atom catalysis, and computational spectroscopy is expected to play a more critical role in future cooperation of simulations and experiments. To better understand the reaction mechanisms of single-atom catalysis, the uniqueness of SACs should be considered more carefully. The potential multiadsorption patterns of reactants and other species in reaction environments may open new reaction channels. Synergetic effects between isolated single atoms and substrates and those within single-atom pairs with different distances could also bring a rich diversity of reaction centers. In terms of possible feedback of theoretical simulations to the experimental studies, simulation results that can quantitatively describe the stability of SACs may help guide their atomically precise preparation. Applying machine-learning methods in the establishment of structure–property relations and the high-throughput screening of SACs can also help suggest promising candidates for experimental validations. Finally, the application of higher level theoretical methodologies like periodic MP2 in studies of single-atom catalysis will bring new prospects to this field, although currently such

kind of works, if any, are still very limited. Given the great achievements and the expected further developments, no one would doubt that there will be a brighter future in the field of single-atom catalysis.

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Notes

The authors declare no competing financial interest.

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